BURIED, FULLY DEPLETABLE, HIGH FILL FACTOR PHOTODIODES

Background of the Invention

5   The present patent application is a continuation-in-part of patent application 09/021,010 the entire contents thereof being incorporated herein by reference.

Field of the Invention

The present invention relates to active pixel solid state photosensors and imagers 10   using CMOS technology.

Description of the Related Art

Active pixel solid state sensors and devices for detecting electromagnetic radiation are well known and in widespread use. When mounted in camera systems, pixel arrays serve as vision or image sensors which produce electrical signals 15   corresponding to the detected light levels. Examples of such photosensors are disclosed in EP739039 and in WO93/19489. These sensors, implemented using CMOS- or MOS-technology, utilize collection junctions which are regions adapted for collecting charges generated by radiation in the semiconductor substrate. The collection junctions are either p-n or n-p junctions, depending on whether the substrate is of p-type or n-type 20   conductivity, respectively.

An active pixel is configured with circuitry integrated in the pixel to amplify the charge that is collected on the light sensitive element or component in the pixel. Active pixels may also be equipped with additional electronics for more elaborate functions, such as filtering, high speed operation, or operation in more extreme illumination 25   conditions. Conversely, passive pixels do not have such circuitry, so they require charge-sensitive amplifiers which are connected to the pixel via a conductive wire or line of metallization. However, one primary drawback of active pixel CMOS or MOS sensors is that a significant part of the pixel surface is used for the detection circuitry, thereby limiting the collection area for each pixel.

30   Because all photon-generated charges within a recombination length from the collection junction have a chance of diffusing to, and being collected by, the junction,

the charge sensitive volume of a collection junction is larger than the junction's depletion layer. Based on this mechanism, a sensor with a small collection junction can have a larger photosensitive volume. For example, photosensors with an apparent front size or photosensitive region of approximately 30 µm diameter can be made with

5 junctions of 3 µm by 2 µm and with a recombination length of 15 µm. However, for active pixels which contain other circuitry (e.g. detection circuitry), some charges that would otherwise have reached the collection junction are instead captured by the junctions or components of the additional circuitry. These charges taken by the pixel's additional circuitry are therefore lost and do not contribute to the detected signal. This

10 is a principal reason for the low fill factor or low sensitivity of active pixel sensors.

It is known in the art that photodiode dark current (i.e. current not caused by detected electromagnetic radiation) is primarily due to thermal generation of charge carriers at the edges of the photodiode, or at the interface between the silicon and SiO_2. This dark current can be significantly reduced by a method called "inversion mode" or

15 "all phase pinning" in which the Si-SiO_2 interface is brought into inversion by applying a dopant layer to the surface of the photodiode. This dopant layer prevents contact between the buried channel (i.e. the useful collecting junction) and the Si-SiO_2 interface. This method typically reduces the dark current two orders of magnitude.

An example of an active pixel device prior to the present invention is

20 represented by Lee et al., U.S. Pat. No. 5,625,210 "ACTIVE PIXEL SENSOR INTEGRATED WITH A PINNED PHOTODIODE", which illustrates integrating a n-well CMOS pinned photodiode with a transfer gate into an image sensing element of an active pixel element. As shown in **Figure 1**, the p-type substrate **24** forms a p-n photodiode with the n-region **22** which becomes the photoactive element and stores the

25 photoelectrons created by photons impinging onto the pixel. "Burying" the n-well **22** under a p+ pinning region **20** confines the collected photoelectrons in the deeper n-region. Because the photodiode junction is then prevented from touching the Si-SiO_2 interface **30**, the generation of dark current at generation centers at the interface is suppressed. The electrostatic potential created by the pinning dopant region **20** also

30 reduces the influence of any oxide layer charge on the junction potential. Such photodiodes also have better ionization radiation tolerances .

The pinning dopant region **20** of the photodiode also reduces the capacitance of the collection junction, which reduces the kTC noise of the sensor and the possibility of "ghost" images; i.e. relics of prior frames' bright images in subsequent dark frames. The so-called kTC noise, one of the primary sources of noise in imaging sensors, is typically expressed as an amount of noise charge (i.e. uncertainty of the measurements of the photo-generated charge), and it is proportional to the square root of the capacitance of the collection junction. Therefore any reduction of capacitance equates to a reduction of the kTC noise. The pinning dopant layer **20** reduces the capacitance of the collection junction by raising the minimum of the electrostatic potential well in which the photoelectrons are confined. When this potential well is shallower than the transfer bias of the transfer gate **28**, the photodiode can be completely depleted or reset in a shorter amount of time. Therefore, with a sufficient reduction of the sensor's capacitance by the pinning dopant layer **20**, all of the photoelectrons can be transferred to the detection circuitry n-well **26** by turning on the transfer gate **28**, leaving no charge in the potential well to contribute to a later frame's image.

A MOSFET is formed by the transfer gate **28** above the p-type substrate **24** between the charge collection n-well **22** and the CMOS detection circuitry n-well **26**. Application of a sufficient voltage to the transfer gate **28** forms a depletion region between the two n-wells **22** and **26**, thereby providing an n-channel for charge transfer between the pinned photodiode and the floating diffusion CMOS detection circuitry. The transfer gate **28** is the gate or electrode that controls the conditional transfer of charges between a photodiode (or other structure containing charge, e.g. a storage gate) to a register. The sole function of the transfer gate **28** is as a switch, which creates the charge transfer channel when appropriately biased.

Summary of the Invention

However, the present inventors recognized several disadvantages inherent in the pinned photodiode technology described in the prior art. First, precise manufacturing steps are crucial for proper performance of the pinned photodiode. While the pinning dopant region **20** and the n-well **22** are self-aligned with one another, a small misalignment between the transfer gate and the underlying n-wells **22** and **26** will drastically impair device performance. If the transfer gate **28** does not extend to the

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edges of both the n-wells **22** and **26**, then there will be a p-type barrier to charge transfer, which can significantly reduce or eliminate the charge transfer, even when the transfer gate is fully biased. Second, some of the photoelectrons that otherwise would have reached the photodiode's n-well **22** are instead collected by other circuitry (e.g. detection circuitry) in the proximity of the collection junction. In other words, the effective fill factor of the n-well **22** is rather limited because photoelectrons which would otherwise contribute to the signal are captured by the potential wells of the surrounding circuitry. And third, while low capacitance photodiodes have low kTC noise levels and high transfer efficiencies which minimize "ghost" images, they also have small areas, and thus small light collection volumes.

The present invention provides an alternative device structure which overcomes the disadvantages of the devices described in the prior art while achieving some of their favorable characteristics. By utilizing a dual-purpose electrode (rather than a transfer gate) which extends beyond the edge of the collection photodiode, the present invention overcomes the sensitivity of device performance on small misalignments between manufacturing steps. Furthermore, the collection-mode potential of the dual-purpose electrode can be adjusted to achieve charge confinement and enhanced collection efficiency, reducing or eliminating the need for the additional p+ dopant layer found in the prior art. Finally, the present invention enhances the fill factor of the photodiode by shielding the photon-created charge carriers formed in the substrate from the potential wells of the surrounding circuitry.

One aspect of the present invention involves a detector of electromagnetic radiation. The detector has a semiconductor substrate with dopants of a first conductivity type at a first concentration density, and an insulating layer at its surface. A collection region with dopants of a second conductivity type opposite the first conductivity type at a second concentration density is formed in the surface region of the semiconductor substrate. A dual-purpose electrode is formed on the insulating layer, extending over both the surface of at least part of the collection region and over at least part of the substrate. Preferably, the collection region forms a junction with the semiconductor substrate. In one embodiment, the junction formed is a photodiode.

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In one embodiment, the substrate further has a barrier region of the first conductivity type with a concentration density of dopants being higher than the concentration density of dopants in the substrate. In another embodiment, the barrier region extends at least partly under the dual purpose electrode. In yet a further embodiment, a detection region with dopants of the second conductivity type at a third concentration density is formed in the surface region of the semiconductor substrate, not bordering the collection region and being connected to read-out electronics.

In another embodiment, the surface regions of the semiconductor substrate beyond the collection region are barrier regions which have dopants of the first conductivity type at a concentration density larger than the concentration density of the semiconductor substrate, and the read-out electronicsare are formed within shielding regions. Preferably, at least part of the charge carriers that are generated in the semiconductor substrate underneath the shielding regions are collected by the collection region.

In yet another embodiment, the a pinning region with dopants of the first conductivity type at a fourth concentration density is within the surface region. Preferably, the pinning region is not covered by the dual purpose electrode. In one embodiment, the pinning region is aligned with the dual-purpose electrode, and extends along the collection region.

Another aspect of the present invention involves a method of making a detector of electromagnetic radiation. The method involves providing a semiconductor substrate with dopants of a first conductivity type at a first concentration density, and with an insulating layer at its surface, forming a collection region by introducing dopants of a second conductivity type which is opposite the first conductivity type at a second concentration density region into the surface region of the semiconductor substrate, and forming a dual-purpose electrode on the insulating layer with the dual-purpose electrode extending over the surface of the collection region.

Brief Description of the Drawings

Figure 1 illustrates a prior art pinned-diode photodiode assembled on a p-type semiconductor substrate.

Figure 2 illustrates a detector of electromagnetic radiation in accordance with a first embodiment of the present invention with a dual-purpose electrode.

Figure 3 illustrates a detector in accordance with a second embodiment of the present invention.

Figure 4 illustrates a detector in accordance with a third embodiment of the present invention.

<u>Detailed Description of the Preferred Embodiment</u>

The present invention is applicable to any active or passive pixel structures.

Figure 2 illustrates a first embodiment of a detector of electromagnetic radiation of the present invention formed in a semiconductor substrate **24** with dopants of a first conductivity type at a first concentration density. In the preferred embodiment of **Fig. 2**, the semiconductor substrate **24** is a p-type silicon substrate. An insulation layer **30**, such as silicon dioxide SiO_2, is specifically formed on the substrate surface. As depicted in **Fig. 2**, the detector has a collection region **22** formed in the surface region of the semiconductor substrate **24**, with dopants of a second conductivity type which is opposite to the first conductivity type at a second concentration density. This collection region **22** is illustrated in **Fig. 2** to be an n-well, and it forms a photodiode junction with the semiconductor substrate **24**. The detector has a first shielding region **42a** and a second shielding region **42b**, each which have dopants of the first conductivity type at a concentration density larger than the concentration density of the semiconductor substrate **24**. As illustrated in **Fig. 2**, the shielding regions **42a, b** are two p-wells. In the second shielding region **42b**, a detection region **26** is formed in the surface region of the semiconductor substrate **24** with dopants of the second conductivity type at a third concentration density. This detection region **26** does not border the collection region **22**, and it is coupled to detection circuitry **32**. The detection region **26** and the collection region **22** define a barrier region **34** between them. In **Fig. 2**, this detection region **26** is an n-plus well, and the barrier region **34** is part of the shielding region **42b** which borders the collection region **22**. A dual-purpose electrode **40** is formed on the insulation layer **30**, extending over the surface of the collection region **22**, and fully across the barrier region **34** to the edge of the detection region **26**.

Persons skilled in the art recognize that the first conductivity type can be either n-type or p-type, and that there are many values of the first, second, and third concentration densities which are compatible with the present invention. The shielding regions **42a, 42b**, the collection region **22** and the detection region **26** are all formed using techniques well understood in the art, such as diffusion or implantation. Similarly, the dual-purpose electrode **40** and insulation layer **30** are formed in conventional manners. The dual-purpose electrode **40** extends across the surface of the collection region **22**, and fully across a portion of the shielding region **42b** which extends to the surface of the substrate **24**. The dual-purpose electrode **40** extends across the identified portion of the shielding region **42b** to an edge of the detection region **26**. The photocollection junction of the present invention can be a photodiode, but also a junction that consists essentially of a depletion layer or inversion layer to the semiconductor substrate (e.g. surface channel CCD), or that consists essentially of a (partially) depleted buried channel to the semiconductor substrate or surface (e.g. buried channel CCD). Such structures are typically used in CCDs, charge injection devices, photogates, or similar structures. These are called "virtual junctions," since they have the same functionality as a physical n-p junction while collecting photogenerated charge carriers.

The shielding regions **42a, b** shield the photoelectrons created in the substrate **24** from the potential of any oxide regions or detection regions **26**. The electrostatic barrier formed at the interface between the shielding regions **42a, b** and the substrate **24** prevents charges generated underneath the sheilding regions **42a, b** from diffusing into the junctions or other structures of the active pixel's additional electronics. There is no such electrostatic barrier present underneath the collection region **22**, so it can consequently gather charges that are generated under the other electronic components. The collection junction of the preferred embodiment has a near 100% fill factor, which means that nearly the whole surface of the pixel that is exposed to light contributes to the pixel's detected signal. Therefore, the photodiode can have a small junction area and a small capacitance, while having a large collecting volume.

When the substrate **24** is exposed to light, electrons are present. When the dual-purpose electrode **40** is at a low voltage, it causes an electrostatic potential which

collects electrons created in the substrate **24** to a region **44** of the collection region **22**. The confinement minimizes the recombination of the collected charges with the electronic states of the surface of the collection region **22**. Additionally, this confinement reduces the influence of any oxide layer charge on the junction potential.
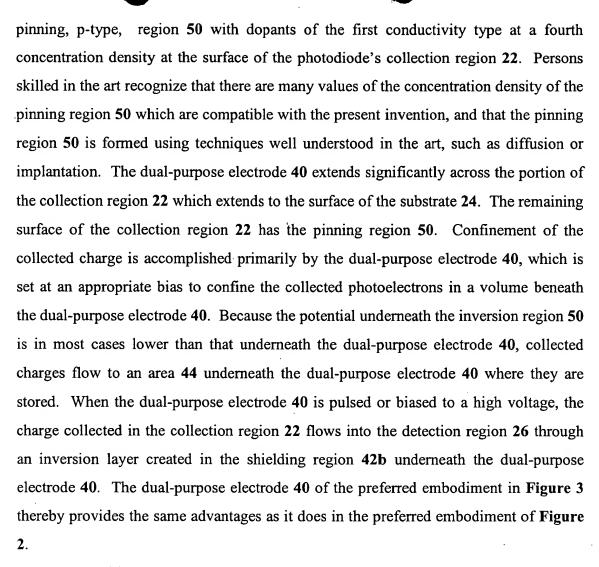
5   When the dual-purpose electrode **40** is biased to a high voltage, the charge collected in the collection region **22** flows into the detection region **26** through an inversion layer created in the shielding region **42b** underneath the dual-purpose electrode **40**. The high bias of the dual-purpose electrode **40** also reduces the capacitance of the photodiode during the charge transfer to the detection region **26** by

10   making the potential well in the photodiode more shallow. This reduction of capacitance permits faster and more complete charge transfer of the collected charge to the detection region **26**. Therefore, the signal from this preferred embodiment has a small kTC noise component, and the possibility of "ghost" images is reduced.

The structure and functionality of the dual-purpose electrode of the preferred

15   embodiment illustrated in **Fig. 2** is different from the transfer gate of the prior art configurations. The dual-purpose electrode of the preferred embodiment of **Fig. 2** enhances the collection and retention of the photoelectrons, creates the inversion layer for transfer of the collected charge into the detection circuitry, and facilitates this transfer by reducing the capacitance of the photodiode.

20   While complete charge transfer from the photodiode's collection region **22** of fig. 2 to the detection region **26 of fig. 2** is possible in theory, practically there are effects that may cause incomplete charge transfer: The complete transfer does not only depend on the voltage or voltage pulse applied to the gate 40, but also on the voltage present at the receiving node 26 in fig 2. . Normally the V_{th} at the n doped side of the

25   electrode is lower than at the p-dopded side. This effect also is a reason that an amount of charge is retained in the n-region after transfer. As the amount of retained charge is rather constant, it can be neglected in normal sensor operation. This effect is also counteracated by increasing the voltage at 26 and/or making the p-doped part of the electrode shorter: the resulting electric field will facilitate the transfer of electrons.

30   In another embodiment of the photodiode of the present invention, as illustrated in **Figure 3**, the dual-purpose electrode **40** is shorter and is used in conjunction with an

pinning, p-type, region **50** with dopants of the first conductivity type at a fourth concentration density at the surface of the photodiode's collection region **22**. Persons skilled in the art recognize that there are many values of the concentration density of the pinning region **50** which are compatible with the present invention, and that the pinning region **50** is formed using techniques well understood in the art, such as diffusion or implantation. The dual-purpose electrode **40** extends significantly across the portion of the collection region **22** which extends to the surface of the substrate **24**. The remaining surface of the collection region **22** has the pinning region **50**. Confinement of the collected charge is accomplished primarily by the dual-purpose electrode **40**, which is set at an appropriate bias to confine the collected photoelectrons in a volume beneath the dual-purpose electrode **40**. Because the potential underneath the inversion region **50** is in most cases lower than that underneath the dual-purpose electrode **40**, collected charges flow to an area **44** underneath the dual-purpose electrode **40** where they are stored. When the dual-purpose electrode **40** is pulsed or biased to a high voltage, the charge collected in the collection region **22** flows into the detection region **26** through an inversion layer created in the shielding region **42b** underneath the dual-purpose electrode **40**. The dual-purpose electrode **40** of the preferred embodiment in **Figure 3** thereby provides the same advantages as it does in the preferred embodiment of **Figure 2**.

In addition, the pinning region **50** effectively reduces the dark current of the photodiode and increases its ionization radiation tolerance by shielding the detection region **26** from electrons thermally generated at the surface or $Si\text{-}SiO_2$ interface. Such an inversion region **50** thereby permits a photodiode with a larger collection area than would otherwise be feasible.

In another preferred embodiment, as illustrated in **Figure 4**, the dual-purpose electrode **40** is used in conjunction with a p-type region **60**. In contrast to the embodiment of **Fig. 3**, the embodiment illustrated in **Fig. 4** has the p-type region **60** situated to the right of the dual-purpose electrode **40** at the surface of a photodiode's collection region **22**; i.e. between the (single-purpose) electrode **40** and the detection region **26**. As in the embodiment illustrated in **Fig. 3**, the collected charge is collected

in a potential pocket **44** underneath the electrode **40** that is electrostatically induced by the electrode's **40** high bias. However, the electrode **40** is not used to form a channel through which the collected charge is transferred to the detection circuitry **32**. Such a channel is actually the n-type region under the p-type region 60..

In the embodiment illustrated in **Fig.** 4, upon reduction of the bias of electrode **40**, the potential in the region 44 drops, until it drops below the potential underneath the p-type region **60**. The charge will then flow to the higher potential of the detection region **26**. Since there is no barrier region to be traversed by the collected charge, there is no need for a dual-purpose electrode to create an inversion layer. The electrode **40** serves both as a confinement of the collected charge, and as a release element allowing the charge to flow to the detection region **26**. In this preferred embodiment, special care must be taken to ensure that there is no unintended barrier regions formed due to misalignment which would prevent charge transfer to the detection circuitry **32**. Region 60 is a barrier, that has a fixed potential height., As soon as the potential in 44 drops below it, charge carriers from 44 flow to 26.

Although described above in connection with particular embodiments of the present invention, it should be understood that the descriptions of the embodiments are illustrative of the invention and are not intended to be limiting. Various modifications and applications may occur to those skilled in the art without departing from the true spirit and scope of the invention as defined in the appended claims.